

This Page Is Inserted by IFW Operations  
and is not a part of the Official Record

## **BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- BLACK BORDERS
- TEXT CUT OFF AT TOP, BOTTOM OR SIDES
- FADED TEXT
- ILLEGIBLE TEXT
- SKEWED/SLANTED IMAGES
- COLORED PHOTOS
- BLACK OR VERY BLACK AND WHITE DARK PHOTOS
- GRAY SCALE DOCUMENTS

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning documents *will not* correct images,  
please do not report the images to the  
Image Problem Mailbox.**

# **Laser Beam Welding of Polymers with High Power Diode Lasers**

## **Joining Innovation for Micro and Macro Technologies**

U.-A. Russek

Fraunhofer-Institut für Lasertechnik ILT

Steinbachstr. 15, 52074 Aachen, Germany

### **Abstract**

Polymers show several application orientated advantages such as:

- low weight
- resistance to environmental stresses
- freedom of design
- recyclability.

This in turn allows innovative product design and new products. But, new fields of application and enhanced demands require innovations in materials processing. Laser technology opens new manufacturing possibilities. Laser welding of thermoplastic polymers provides several process technical advantages:

- contact-less, spatially defined and well-timed energy introduction
- optically and qualitatively high-grade joints
- tight and reproducible joining of micro components as well as macro parts
- joints free of pores as well as air and water tight while showing high strength but no weld burr (flash)
- stable polymer components as well as thinnest foils and films weldable
- amorphous, crystalline and dissimilar polymers and thermoplastic elastomers are weldable
- welding technology shows excellent integration abilities and automatisisation potentials.

Applications of laser welding of polymers are found in several fields of industry, already :

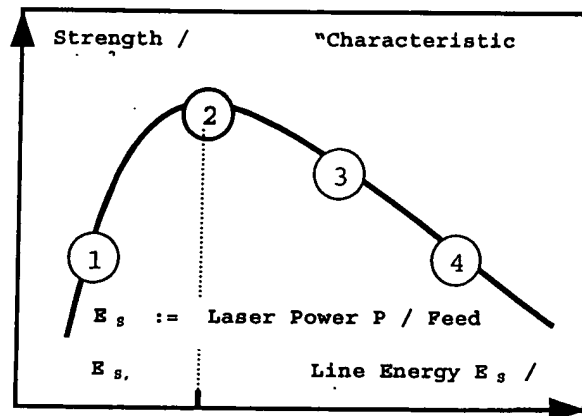
- information and communication technologies
- packaging technologies
- automotive industry
- electrical and electronic industries
- medical technologies
- micro technologies and chemistry
- house hold goods.

Different welding strategies are available, such as serial, mask, quasi-simultaneous and simultaneous welding, while each offers characteristic dis- and advantages. Therefore, the appropriate strategy can be adapted to the current application.

Both scientific and application orientated results concerning laser penetration welding of polymers using high power diode laser are presented in brief. Experimentally obtained results concerning strength of the weld seams as well as the gap bridging capability are presented while comparing it for different process strategies. Furthermore, results from thermodynamic process modelling are illustrated. The modelling considers different steps of approximation up to a complete solution of the real joining geometry while considering the optical properties as well as a gap between the joining partners.

### Process Parameters

To visualise process behaviour and determine process window location the so called “characteristic curve” is commonly used, while displaying strength versus line energy (Fig.1).



**Fig. 1** Characteristic Curve – strength vs. line energy  
 1. Just Light Adhesion - No Good Welding  
 2. Optimal Welding Adjustment  
 3. Optimal Adjustment Left - Bad Welding  
 4. Decomposition - Bad Welding

However, line energy is not a well suited process parameter, since it does not take crucial process influencing aspects into consideration, such as:

- beam shape
- intensity distribution
- process time scales

### Gap Bridging Capability

Gaps between the joining parts influence the joining process, while avoiding a close contact between the joining partners and therefore thermal conduction.

Above all, gaps are problematic while applying serial welding. Gaps are due to, for example :

- manufacturing process (injection pins, shrinkage)
- parts tolerances
- clumsy clamping

It is the goal obtaining explanations for gap bridging behaviour as well as strategies improving gap bridging capability.

While performing extended systematic investigations on gap bridging capability, PP of different carbon black concentrations have been investigated.

Depending on the carbon black concentration and the applied welding strategy, different gap sizes have been bridgeable:

- 150 - 250  $\mu\text{m}$  for a circular spot, serial welding
- 150 - 500  $\mu\text{m}$  for a line shaped spot, serial welding
- larger gap bridging capability for simultaneous welding expectable.

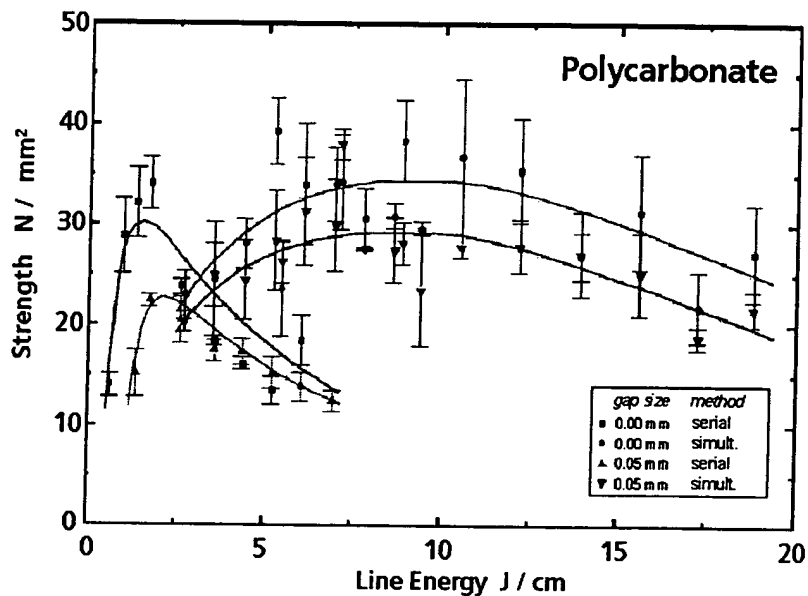


Fig. 3 Strength vs.. line energy, while welding PC serial and simultaneous

In summary,

the lower the c.b.-concentration,

the larger the optical penetration depth,

the larger the (possible) molten volume,

the more moderate the temperature rise,

the larger the gap bridging capability.

BUT this is only valid to a certain extend and

at the expense of line energy necessary for melting

Therefore, for a certain application gap bridging capability becomes predictable, optimum carbon black concentration becomes determinable.

$$\delta_{OPT} \propto 1 / cbc$$

$$\delta_{OPT} \propto \text{molten volume}$$

$$\delta_{OPT} \propto 1 / \nabla T(x,y,z)$$

$$\text{molten volume} \propto \text{bridging capability}$$

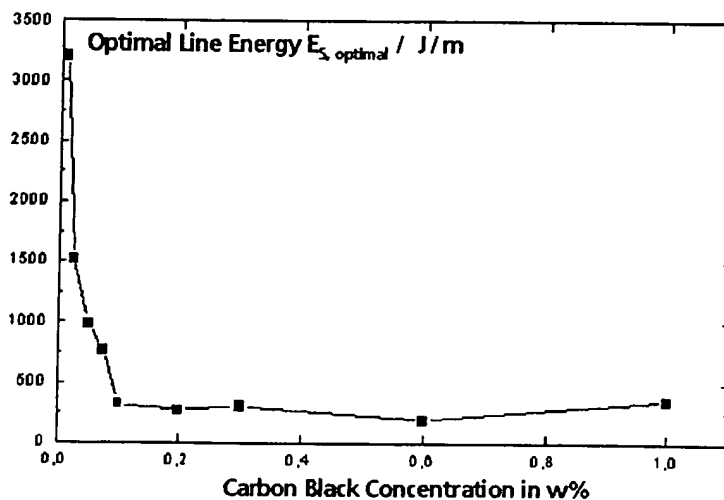
$$\delta_{OPT} \propto E_{S, \text{melting}}$$

### Process Adapted Pigmentation

Optical properties of the joining partners are very crucial for reliable process realisation.

There are different opportunities to influence the optical properties:

- Scattering behaviour is influenced by the size, distribution and nature of scattering centres. Scattering increases line energy necessary. The higher crystallinity, the more beam broadening. By an laser process adapted manufacturing process of the joining partners, the scattering can be influenced.
- The optical penetration depth of a joining partner depends on the carbon black concentration (see above and Fig. 4).



**Fig. 4** Optimal line energy vs. carbon black concentration

The lower the carbon black concentration, the higher the line energy necessary for welding.  
The higher the carbon black concentration, the smaller the optical penetration depth.

- Infrared absorbers (IRA) offer the possibility to adapt absorption behaviour of the joining parts to the applied wavelength without influencing the colour of the joining parts.

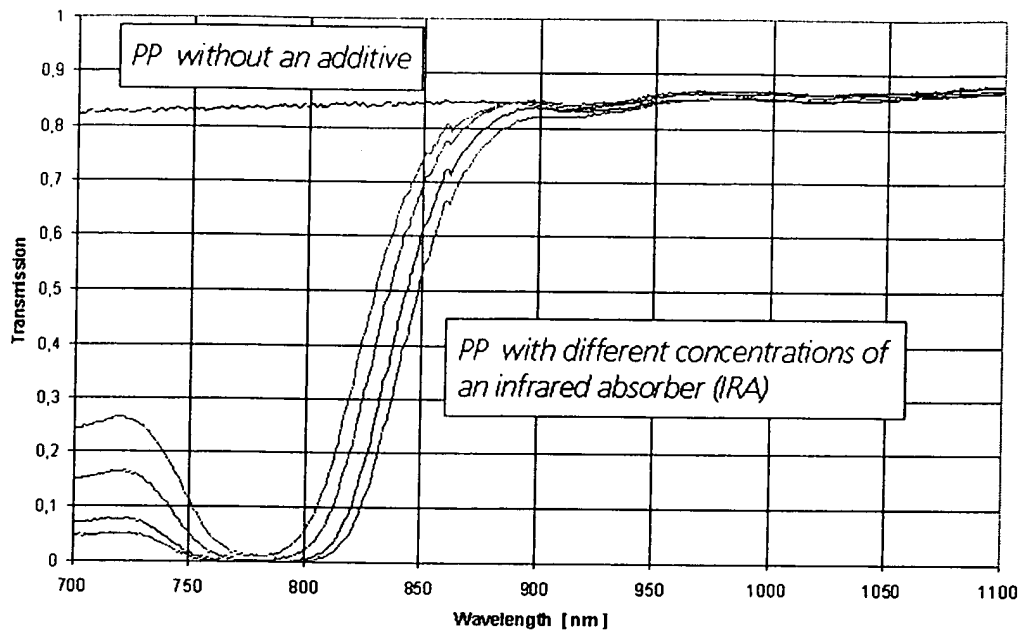


Fig. 5 Spectrum of PP with and without infrared absorbers (IRA)

### Thermodynamic Process Modelling

The energy density distribution, the temperature distribution as well as the volume extension of flat test specimen of Polypropylene resulting from the absorption of the laser radiation are calculated.

The equation of energy conservation is solved for different steps of approximation to indicate the influence of the convective as well as of the diffusive heat flow on the energy density distribution.

While looking only at the absorbing joining partner it turned out if the feed rate is sufficient high the energy distribution is mainly caused by the convective heat flow. This means, the absorbed energy is compensated by the convective heat flow. Furthermore, in this case the energy distribution is mainly depended on the line energy.

Also a borderline case is shown. Although the line energy is kept constant, while laser power and feed rate are decreased correspondingly, the energy distribution is caused by the convective as well as the diffusive heat flow.

The input of heat increases the volume of the absorbing polymer. While looking on the over lap joint geometry this extension is related to the ability to bridge a gap between the joining partners. The extension of the heated polymer as well as the heat flow into the transparent joining partner if gap bridging occurs are calculated. Therefore, obtaining a measure for gap bridging capability. Calculations offer possibility to determine the process window.

For example, while choosing a laser power of 22 W, a feed rate of 7 m/min corresponding to a line energy of 193 J/m, a gap of smaller than 40  $\mu\text{m}$  will be bridged and joining may be possible. These calculations offer the possibility to determine the process window.

The developed programs can also be used for other polymers than Polypropylene, if the necessary material data are available.

Fig. 6 shows the results for thermodynamic process modelling of serial welding of PP, while the energy density distribution  $E$  in  $\text{J}/\text{m}^3$  in cross sectional cuts is depicted for the above mentioned borderline case.

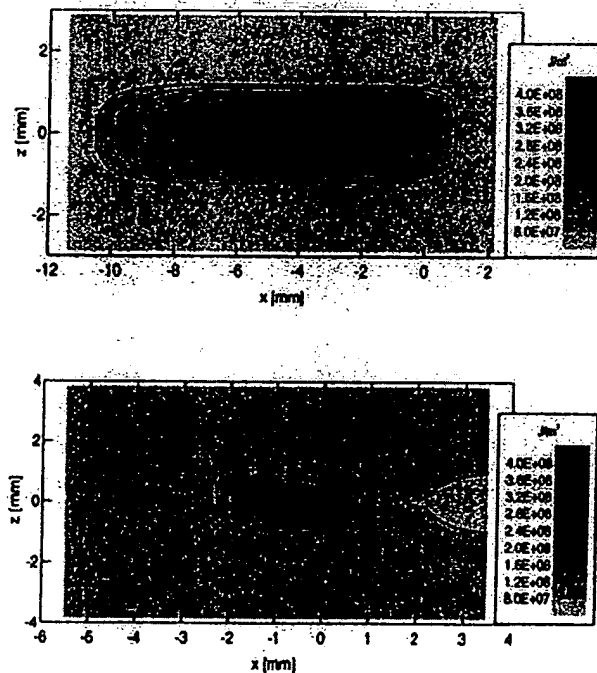
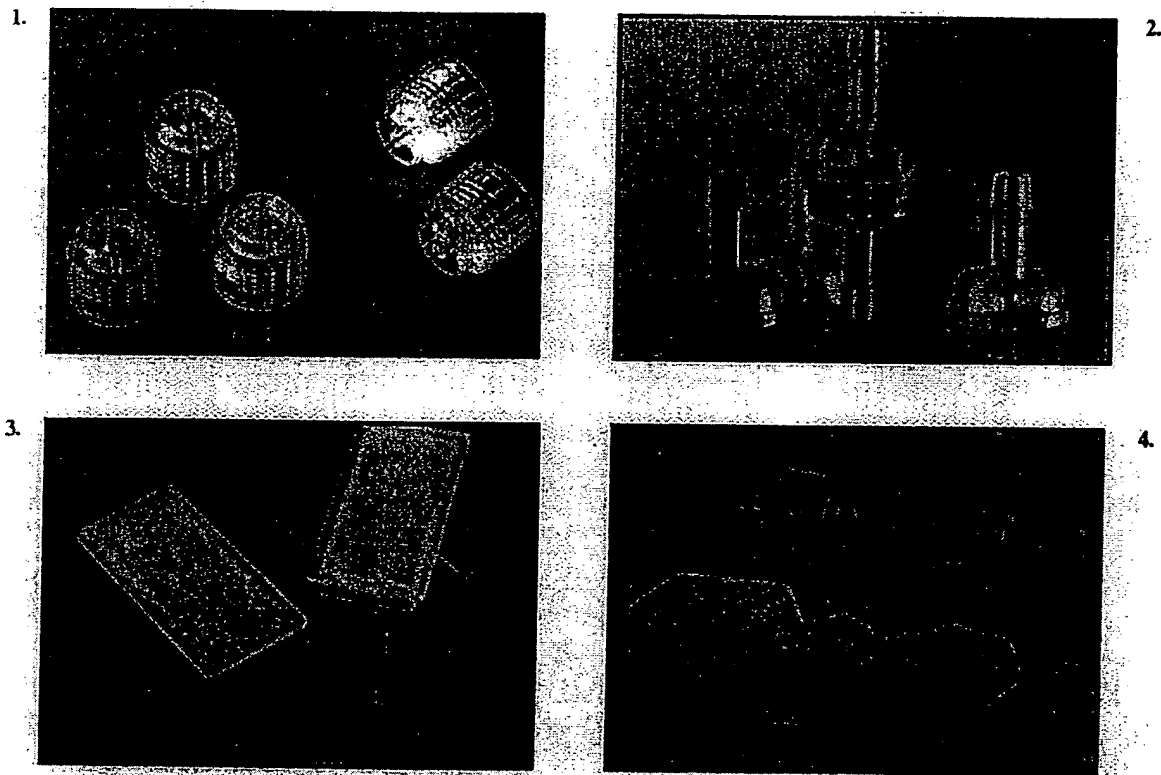


Fig. 6 Energy density distribution - considering the same line energy generated by different power and feed rate

a.	$P = 22,5 \text{ W}$	$v_s = 7 \text{ m / min}$	$E_s = 193 \text{ J / m}$
b.	$P = 3,2 \text{ W}$	$v_s = 1 \text{ m / min}$	$E_s = 193 \text{ J / m}$

## Applications

Performed applications of real, technical components are illustrated in the following pictures, while proofing the industrial implementation capability as well as the advantages of a novel technology.



**Fig. 7** Application of laser beam welding of polymers

1. Medical Injections, Polymer-Metal Joining

2. Filter Cases of Motor Vehicle

3. Simultaneously Welded Closed Polymer Box, Burst Pressure: 8 bar, Process Time:  $0.3 < t < 1$  s

4. Liquid Tank of Automotive Industry (Glass Fiber Reinforced Polymer)



### Acknowledgements

This poster presents results gained from the Polyweld Project. This is a BRITE EURAM project aiming at the development of laser welding as a new joining technique for polymer materials. The European Commission is acknowledged for financial support under "TMT/SMT" programs (1994-1998). The Polyweld Project started in 1998 as BRITE EURAM project BE 97-4625, contract number: BRPR-CT-0634 and has ended in May 2001.

This poster also presents results of the German Project "Modulare Diodenlaser-Strahlwerkzeuge – optische Schweißzange – optische Schere". This is a project founded by the BMBF, while focusing on novel high power diode laser devices as well as their application within the German industry. The BMBF is acknowledged for financial support under the BMBF number 13N7377/2. The project has been started in 1998 and ends in 2003.

### Meet the Author

- 86 – 90      Study of Physical Engineering at FH Jülich, Germany  
Thesis: Basics of Excimer Laser Applications – Set-Up, Operation as well as Applications of an Excimer Laser (performed at FH Jülich)
- 90 – 98      Study of Physics at RWTH Aachen, Germany, and at the Univ. of Michigan, USA  
Thesis: Passive Pulse Shaping of Femtosecond Laser Pulses using a Liquid Crystal Spatial Light Modulator (performed at the Center for Ultrafast Optical Science, University of Michigan, USA)

Since 10 / 98 U.-A. Russek is a PhD student at the RWTH Aachen, Germany, while working at the "Fraunhofer-Institut für Lasertechnik ILT", Aachen, Germany, in the group laser materials processing of polymers and papers, which he is leading since 9 / 00.